Direct neutralino searches in the NMSSM with gravitino LSP in the degenerate scenario

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Abstract

In the present work a two-component dark matter model is studied adopting the degenerate scenario in the R-parity conserving NMSSM. The gravitino LSP and the neutralino NLSP are extremely degenerate in mass, avoiding the BBN bounds and obtaining a high reheating temperature for thermal leptogenesis. In this model both gravitino (absolutely stable) and neutralino (quasi-stable) contribute to dark matter, and direct detection searches for neutralino are discussed. Points that survive all the constraints correspond to a singlino-like neutralino.

1 Introduction

There is accumulated evidence both from astrophysics and cosmology that about 1/4 of the energy budget of the universe consists of so called dark matter, namely a component which is non-relativistic and neither feels the electromagnetic nor the strong interaction. For a review on dark matter see e.g. [1]. Although the list of possible dark matter candidates is long (for a nice list see [2]), it is fair to say that the most popular dark matter candidate is the lightest supersymmetric particle (LSP) in supersymmetric models with R-parity conservation [3]. For supersymmetry and supergravity see [4]. The simplest supersymmetric extension of the standard model that solves the μ problem [5] is the next-to-minimal supersymmetric standard model (NMSSM) [6]. If we do not consider the axion [7] and the axino [8], the superpartners that have the right properties for playing the role of cold dark matter in the universe are the gravitino and the lightest neutralino. By far the most discussed case in the literature is the case of the neutralino (see the classic review [9]), probably because of the prospects of detection. However, in the case in which neutralino is assumed to be the only dark matter component, one has to face the fine-tuning problem and the gravitino problem [10]. In most of the parameter space the neutralino relic density turns out to be either too small or too large [11]. Furthermore, unstable gravitinos will undergo late-time cascade decays to a neutralino LSP. These decays will destroy the light element abundances built up in BBN, unless $T_R < 10^5$ GeV [12], which posses serious difficulties to the thermal leptogenesis scenario [13]. If, on the other hand, gravitino is the LSP and therefore stable, playing the role of cold dark matter in the universe, it is then the neutralino that will undergo late time decays into gravitino and hadrons, and the gravitino problem is re-introduced [14].

It has been shown that in the degenerate scenario [15] the BBN and CMB constraints are avoided, and high values of the reheating temperature are obtained compatible with thermal leptogenesis. Here we focus on the scenario in which the masses of the gravitino LSP and neutralino NLSP are extremely degenerate in mass. Under this assumption neutralino becomes quasi-stable taking part of cold dark matter of the universe together with gravitino, today is still around and can be seen in direct detection searches experiments.

This article is organized as follows. In the next section we present the theoretical framework. In section 3 we discuss all the relevant constraints from colliders and from cosmology, and we show our results. Finally, we conclude.

2 Theoretical framework

In what folows we review in short the particle physics model, namely the cNMSSM, as well as the gravitino production mechanisms.

2.1 Basics of cNMSSM

The most straightforward extension of standard model (SM) of particle physics based on SUSY is the minimal supersymmetric standard model (MSSM) [16]. It is a supersymmetric gauge theory based on the SM gauge group with the usual representations (singlets, doublets, triplets) and on $\mathcal{N} = 1$ SUSY. Excluding gravity, the massless representations of the SUSY algebra are a chiral and a vector supermultiplet. The gauge bosons and the gauginos are members of the vector supermultiplet, while the matter fields (quarks, leptons, Higgs) and their superpartners are members of the chiral supermultiplet. The Higgs sector in the MSSM is enhanced compared to the SM case. There are now two Higgs doublets, H_u, H_d, (or H_1, H_2) for anomaly cancelation

requirements and for giving masses to both up and down quarks. After electroweak symmetry breaking we are left with five physical Higgs bosons, two charged $H^{\pm}$ and three neutral A, H, h (h being the lightest). Since we have not seen any superpartners yet, SUSY has to be broken. In MSSM, SUSY is softly broken by adding to the Lagrangian terms of the form

- Mass terms for the gauginos $\tilde{g}_i$, M_1, M_2, M_3

$$M\tilde{g}\tilde{g} \tag{1}$$

- Mass terms for sfermions $\tilde{f}$

$$m_{\tilde{f}}^2 \tilde{f}^{\dagger}\tilde{f} \tag{2}$$

- Masses and bilinear terms for the Higgs bosons H_u, H_d

$$m_{H_u}^2 H_u^{\dagger} H_u + m_{H_d}^2 H_d^{\dagger} H_d + B\mu(H_u H_d + h.c.) \tag{3}$$

- Trilinear couplings between sfermions and Higgs bosons

$$AY\tilde{f}_1 H \tilde{f}_2 \tag{4}$$

In the unconstrained MSSM there is a huge number of unknown parameters [17] and thus little predictive power. However, motivated by the grand unification idea, the constrained MSSM (CMSSM) assumes that gaugino masses, scalar masses and trilinear couplings have (separately) a common, universal value at the GUT scale, like the gauge coupling constants do. CMSSM is therefore a framework with a small controllable number of parameters, and thus with much more predictive power. In the CMSSM there are four parameters, $m_0, m_{1/2}, A_0, tan\beta$, which are explained below, plus the sign of the μ parameter from the Higgs sector. The magnitude of μ, as well as the B parameter mentioned above, are determined by the requirement for a proper electroweak symmetry breaking. However, the sign of μ remains undetermined. The other four parameters of the CMSSM are related by

- Universal gaugino masses

$$M_1(M_{GUT}) = M_2(M_{GUT}) = M_3(M_{GUT}) = m_{1/2} \tag{5}$$

- Universal scalar masses

$$m_{\tilde{f}_i}(M_{GUT}) = m_0 \tag{6}$$

- Universal trilinear couplings

$$A_{ij}^u(M_{GUT}) = A_{ij}^d(M_{GUT}) = A_{ij}^l(M_{GUT}) = A_0\delta_{ij} \tag{7}$$

- $$tan\beta \equiv \frac{v_1}{v_2} \tag{8}$$

  where v_1, v_2 are the vevs of the Higgs doublets and $M_{GUT} \sim 10^{16}\ GeV$ is the Grand Unification scale.

Unfortunately, the CMSSM suffers from the so-called μ problem [5]. This problem is elegantly solved in the framework of the next-to-minimal supersymmetric standard model (NMSSM) [6]. In addition to the MSSM Yukawa couplings for quarks and leptons, the NMSSM superpotential contains two additional terms involving the Higgs doublet superfields, H_1 and H_2, and the new superfield S, a singlet under the SM gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$ [18]

$$W = \epsilon_{ij} \left(Y_u \, H_2^j \, Q^i \, u + Y_d \, H_1^i \, Q^j \, d + Y_e \, H_1^i \, L^j \, e \right) - \epsilon_{ij} \lambda \, S \, H_1^i H_2^j + \frac{1}{3} \kappa S^3 \tag{9}$$

where we take $H_1^T = (H_1^0, H_1^-)$, $H_2^T = (H_2^+, H_2^0)$, i, j are $SU(2)$ indices, and $\epsilon_{12} = 1$. In this model, the usual MSSM bilinear μ term is absent from the superpotential, and only dimensionless trilinear couplings are present in W. However, when the scalar component of S acquires a VEV, an effective interaction $\mu H_1 H_2$ is generated, with $\mu \equiv \lambda \langle S \rangle$.

Finally, the soft SUSY breaking terms are given by [18]

$$\begin{aligned} -\mathcal{L}_{\text{soft}} = & m_{\tilde{Q}}^2 \, \tilde{Q}^* \, \tilde{Q} + m_{\tilde{U}}^2 \, \tilde{u}^* \, \tilde{u} + m_{\tilde{D}}^2 \, \tilde{d}^* \, \tilde{d} + m_{\tilde{L}}^2 \, \tilde{L}^* \, \tilde{L} + m_{\tilde{E}}^2 \, \tilde{e}^* \, \tilde{e} \\ & + m_{H_1}^2 \, H_1^* \, H_1 + m_{H_2}^2 \, H_2^* H_2 + m_S^2 \, S^* S \\ & + \epsilon_{ij} \, \left(A_u \, Y_u \, H_2^j \, \tilde{Q}^i \, \tilde{u} + A_d \, Y_d \, H_1^i \, \tilde{Q}^j \, \tilde{d} + A_e \, Y_e \, H_1^i \, \tilde{L}^j \, \tilde{e} + \text{H.c.} \right) \\ & + \left(-\epsilon_{ij} \lambda \, A_\lambda S H_1^i H_2^j + \frac{1}{3} \kappa \, A_\kappa \, S^3 + \text{H.c.} \right) \\ & - \frac{1}{2} \, \left(M_3 \, \lambda_3 \, \lambda_3 + M_2 \, \lambda_2 \, \lambda_2 + M_1 \, \lambda_1 \, \lambda_1 + \text{H.c.} \right) \end{aligned} \tag{10}$$

Clearly, the NMSSM is very similar to the MSSM. Despite the similarities between the two particle physics models, the Higgs sector as well as the neutralino mass matrix and mass eigenstates in the NMSSM are more complicated and richer compared to the corresponding ones in the MSSM.

In particular, in the Higgs sector we have now two CP-odd neutral, and three CP-even neutral Higgses. We make the assumption that there is no CP-violation in the Higgs sector at tree level, and neglecting loop level effects, the CP-even and CP-odd states do not mix. We are not interested in the CP-odd states, while the CP-even Higgs interaction and physical eigenstates are related by the transformation

$$h_a^0 = S_{ab} H_b^0 \tag{11}$$

where S is the unitary matrix that diagonalises the CP-even symmetric mass matrix, $a, b = 1, 2, 3$, and the physical eigenstates are ordered as $m_{h_1^0} \lesssim m_{h_2^0} \lesssim m_{h_3^0}$.

In the neutralino sector the situation is again more involved, since the fermionic component of S mixes with the neutral Higgsinos, giving rise to a fifth neutralino state. In the weak interaction basis defined by $\Psi^{0T} \equiv \left(\tilde{B}^0 = -i\lambda', \tilde{W}_3^0 = -i\lambda_3, \tilde{H}_1^0, \tilde{H}_2^0, \tilde{S} \right)$, the neutralino mass terms in the Lagrangian are [18]

$$\mathcal{L}_{\text{mass}}^{\tilde{\chi}^0} = -\frac{1}{2} (\Psi^0)^T \mathcal{M}_{\tilde{\chi}^0} \Psi^0 + \text{H.c.} \,, \tag{12}$$

with $\mathcal{M}_{\tilde{\chi}^0}$ a 5×5 matrix,

$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z \sin\theta_W \cos\beta & M_Z \sin\theta_W \sin\beta & 0 \\ 0 & M_2 & M_Z \cos\theta_W \cos\beta & -M_Z \cos\theta_W \sin\beta & 0 \\ -M_Z \sin\theta_W \cos\beta & M_Z \cos\theta_W \cos\beta & 0 & -\lambda s & -\lambda v_2 \\ M_Z \sin\theta_W \sin\beta & -M_Z \cos\theta_W \sin\beta & -\lambda s & 0 & -\lambda v_1 \\ 0 & 0 & -\lambda v_2 & -\lambda v_1 & 2\kappa s \end{pmatrix} \tag{13}$$

The above matrix can be diagonalised by means of a unitary matrix N

$$N^* \mathcal{M}_{\tilde{\chi}^0} N^{-1} = \mathrm{diag}(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_3^0}, m_{\tilde{\chi}_4^0}, m_{\tilde{\chi}_5^0}) \tag{14}$$

where $m_{\tilde{\chi}_1^0}$ is the lightest neutralino mass. Under the above assumptions, the lightest neutralino can be expressed as the combination

$$\tilde{\chi}_1^0 = N_{11}\tilde{B}^0 + N_{12}\tilde{W}_3^0 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0 + N_{15}\tilde{S} \tag{15}$$

In the following, neutralinos with $N_{11}^2 > 0.9$, or $N_{15}^2 > 0.9$, will be referred to as bino- or singlino-like, respectively.

Similarly to the CMSSM, in the constrained next-to-minimal supersymmetric standard model the universality of $m_0, A_0, m_{1/2}$ at the GUT scale is again assumed, with the only parameters now being [19]

$$tan\beta, m_0, A_0, m_{1/2}, \lambda, A_k$$

and the sign of the μ parameter can be chosen at will.

We end the discussion on the particle physics model here, by making a final remark regarding the differences between the CMSSM and the cNMSSM. In the CMSSM the lightest neutralino is mainly a bino in most of the parameter space, and low values of m_0 are disfavored because they lead to charged sleptons that are lighter than the neutralino χ_1^0, while in the cNMSSM the lightest neutralino is mainly a singlino in large regions of the parameter space, thanks to which the charged LSP problem can be avoided [19]. Furthermore, in the cNMSSM there are more mechanisms that contribute to the neutralino relic density [19].

2.2 Gravitino production

In the usual case (not in the degenerate scenario) where the neutralino decays into a gravitino and standard model particles with a lifetime typically in the range $(10^4 - 10^8)\ sec$, for the gravitino abundance we take the relevant production mechanisms into account and impose the cold dark matter constraint [20]

$$0.1097 < \Omega_{cdm}h^2 = \Omega_{3/2}h^2 < 0.1165 \tag{16}$$

At this point it is convenient to define the gravitino yield, $Y_{3/2} \equiv n_{3/2}/s$, where $n_{3/2}$ is the gravitino number density, $s = h_{eff}(T)\frac{2\pi^2}{45}T^3$ is the entropy density for a relativistic thermal bath, and h_{eff} counts the relativistic degrees of freedom. The gravitino abundance $\Omega_{3/2}$ in terms of the gravitino yield is given by

$$\Omega_{3/2}h^2 = \frac{m_{\tilde{G}} s(T_0) Y_{3/2} h^2}{\rho_{cr}} = 2.75 \times 10^8 \left(\frac{m_{\tilde{G}}}{\mathrm{GeV}}\right) Y_{3/2}(T_0) \tag{17}$$

where we have used the values

$$\begin{aligned} T_0 &= 2.73K = 2.35 \times 10^{-13}\ \mathrm{GeV} && (18)\\ h_{eff}(T_0) &= 3.91 && (19)\\ \rho_{cr}/h^2 &= 8.1 \times 10^{-47}\ \mathrm{GeV}^4 && (20) \end{aligned}$$

The total gravitino yield has two contributions, namely one from the thermal bath, and one from the out-of-equillibrium NLSP decay.

$$Y_{3/2} = Y_{3/2}^{TP} + Y_{3/2}^{NLSP} \tag{21}$$

The contribution from the thermal production has been computed in [21, 22, 23]. In [21] the gravitino production was computed in leading order in the gauge coupling g_3, in [22] the thermal rate was computed in leading order in all Standard Model gauge couplings g_Y, g_2, g_3, and in [23] new effects were taken into account, namely: a) gravitino production via gluon $\rightarrow$ gluino + gravitino and other decays, apart from the previously considered $2 \rightarrow 2$ gauge scatterings, b) the effect of the top Yukawa coupling, and c) a proper treatment of the reheating process. Here we shall use the result of [21] since the corrections of [22, 23] do not alter our conclusions. Therefore the thermal gravitino production is given by

$$Y_{3/2}^{TP} = 0.29 \times 10^{-12} \left(\frac{T_R}{10^{10} \text{ GeV}} \right) \left(1 + \frac{1}{3} \frac{m_{\tilde{g}}^2}{m_{\tilde{G}}^2} \right) \tag{22}$$

or, approximately for a light gravitino, $m_{\tilde{G}} \ll m_{\tilde{g}}$

$$Y_{3/2}^{TP} \simeq 10^{-13} \left(\frac{T_R}{10^{10} \text{ GeV}} \right) \left(\frac{m_{\tilde{g}}}{m_{\tilde{G}}} \right)^2 \tag{23}$$

with $m_{\tilde{G}}$ the gravitino mass and $m_{\tilde{g}}$ the gluino mass.

The second contribution to the gravitino abundance comes from the decay of the NLSP

$$\Omega_{3/2}^{NLSP} h^2 = \frac{m_{\tilde{G}}}{m_{NLSP}} \, \Omega_{NLSP} h^2 \tag{24}$$

with m_{NLSP} the mass of the NLSP, and $\Omega_{NLSP} h^2$ the abundance the NLSP would have, had it not decayed into the gravitino. In the limit where $m_{NLSP} \rightarrow m_{\tilde{G}}$ and $\tau_{NLSP} \gg 10^{17}$ *sec* the scenario looks as if one would have a two-component dark matter with the NLSP contribution $\Omega_{NLSP} h^2$, and a gravitino contribution from thermal production only, $Y_{3/2}^{TP}$. Therefore, in the degenerate scenario with $m_{NLSP} \simeq m_{\tilde{G}}$ the WMAP bound becomes

$$0.1097 < \Omega_{cdm} h^2 = \Omega_{NLSP} h^2 + \Omega_{3/2}^{TP} h^2 < 0.1165 \tag{25}$$

where from now on the NLSP is the lightest neutralino, $\chi = NLSP$.

3 Constraints and results

- Spectrum and collider constraints: We have used NMSSMTools [24], a computer software that computes the masses of the Higgses and the superpartners, the couplings, and the relic density of the neutralino, for a given set of the free parameters. We have performed a random scan in the whole parameter space (with fixed $\mu > 0$ motivated by the muon anomalous magnetic moment), and we have selected only those points that satisfy i) theoretical requirements, such as neutralino LSP, correct electroweak symmetry breaking, absence of tachyonic masses etc., and ii) LEP bounds on the Higgs mass, collider bounds on SUSY particle masses, and experimental data from B-physics [25, 26]. For all these good points the lightest neutralino is either a bino or a singlino, and contrary to the case where neutralino is the dark matter particle, here we do not require that the neutralino relic density falls within the allowed WMAP range.

- As we have already mentioned, the total dark matter abundance, and not the neutralino one, should satisfy the cold dark matter constraint [20]

$$0.1097 < \Omega_{cdm} h^2 = \Omega_{\chi} h^2 + \Omega_{3/2}^{TP} h^2 < 0.1165 \tag{26}$$

that relates the reheating temperature after inflation to the gravitino mass as follows

$$0.11 = A(m_{\tilde{G}}, m_{\tilde{g}})T_R + \Omega_\chi h^2 \tag{27}$$

For a given point in the cNMSSM parameter space, the complete spectrum and couplings have been computed, and we are left with two more free parameters, namely the gravitino mass and the reheating temperature after inflation. The gravitino mass is equal essentially to the neutralino mass, and the precise value can be determined if we specify the neutralino lifetime. In the discussion to follow we have used a neutralino lifetime $\tau = 10^{26}\,sec$, although the results are not sensitive to it, and the figures we have produced for different values of the lifetime cannot be distinguished. Finally, the reheating temperature after inflation is obtained from the cold dark matter constraint. The thermal production contribution cannot be larger than the total dark matter abundance, and for this we can already obtain an upper bound on the reheating temperature

$$T_R \leq 4.1 \times 10^9 \left(\frac{m_{\tilde{G}}}{100 \text{ GeV}}\right) \left(\frac{\text{TeV}}{m_{\tilde{g}}}\right)^2 \text{ GeV} \tag{28}$$

Assuming a gluino mass $m_{\tilde{g}} \sim 1$ TeV, we can see that for a heavy gravitino, $m_{\tilde{G}} \sim 100$ GeV, it is possible to obtain a reheating temperature large enough for thermal leptogenesis.

- For neutralino NLSP in the degenerate scenario, the only decay mode is $\chi \to \gamma\tilde{G}$, for which the decay width can be computed once the supergravity Largrangian is known [27], and it is given by [14, 28]

$$\Gamma(\chi \to \gamma\tilde{G}) = \frac{|N_{11}\cos\theta_W + N_{12}\sin\theta_W|^2}{48\pi M_*^2} \frac{m_\chi^5}{m_{\tilde{G}}^2} \left[1 - \frac{m_{\tilde{G}}^2}{m_\chi^2}\right]^3 \left[1 + 3\frac{m_{\tilde{G}}^2}{m_\chi^2}\right] \tag{29}$$

where M_* is the Planck mass, m_χ is the neutralino mass, and θ_W is the weak angle. In the limit where the mass difference $\Delta m \equiv m_\chi - m_{\tilde{G}}$ is much lower than the masses themselves, $\Delta m \ll m_\chi, m_{\tilde{G}}$, the neutralino lifetime becomes

$$\tau = \frac{1.78 \times 10^{13}\ sec}{|N_{11}\cos\theta_W + N_{12}\sin\theta_W|^2} \left(\frac{GeV}{\Delta m}\right)^3 \tag{30}$$

From this formula one can see that for a mostly bino-neutralino a mass difference of 1 MeV is already enough to give a neutralino lifetime larger than the age of the universe.

- Neutralino-Nucleon spin-independent cross-section: LHC is now running and collecting data. Although LHC is a powerful machine to look for physics beyond the standard model, it is known that other facilities are also needed to offer complementary information towards the direction of searching for supersymmetry and identifying dark matter. The gravitino interactions are suppressed by the Planck mass, and therefore direct production of gravitinos at colliders and/or direct detection prospects seem to be hopeless. On the other hand, for a weakly interacting neutralino there are existing as well as future experiments that put experimental limits on the nucleon-neutralino cross-section. The spin-independent cross-section is given by

$$\sigma_{\chi-N} = \frac{4m_r^2}{\pi} f_N^2 \tag{31}$$

where m_r is the Nucleon-neutralino reduced mass, $m_r = m_N m_\chi/(m_N + m_\chi)$, and

$$\frac{f_N}{m_N} = \sum_{q=u,d,s} f_{Tq}^{(N)} \frac{\alpha_q}{m_q} + \frac{2}{27} f_{TG}^{(N)} \sum_{q=c,b,t} \frac{\alpha_{3q}}{m_q} \tag{32}$$

In the above, $f_{TG}^{(N)} = 1 - \sum_{q=u,d,s} f_{Tq}^{(N)}$, we have taken the following values for the hadronic matrix elements [29]:

$$\begin{aligned} f_{Tu}^{(p)} &= 0.020 \pm 0.004\,, \quad f_{Td}^{(p)} = 0.026 \pm 0.005\,, \qquad\qquad f_{Ts}^{(p)} = 0.118 \pm 0.062\,, \\ f_{Tu}^{(n)} &= 0.014 \pm 0.003\,, \quad f_{Td}^{(n)} = 0.036 \pm 0.008\,, \qquad\qquad f_{Ts}^{(n)} = 0.118 \pm 0.062\,. \end{aligned} \tag{33}$$

and α_q is the coupling in the effective Lagrangian

$$\mathcal{L}_{\rm eff} = \alpha_i\, \bar{\chi}\, \chi\, \bar{q}_i\, q_i \tag{34}$$

where $i = 1, 2$ denotes up- and down-type quarks, and the Lagrangian is summed over the three quark generations. The coupling α_q can be decomposed into two parts, $\alpha_q = \alpha_q^h + \alpha_q^{\tilde{q}}$, where the first term is the t-channel exchange of a neutral Higgs (Fig. 1), while the second term is the s-channel exchange of a squark (Fig. 2). The expressions for α_q is terms of the masses and couplings of the model can be found in [18].

Our main results are summarized in the figures below. In Fig. 3 and Fig. 4 we show the Nucleon-neutralino spin-independent cross section (in cm^2) versus neutralino mass and lightest Higgs boson (in GeV) respectively. The blue region corresponds to a bino neutralino, while the green region corresponds to a singlino neutralino, and the curves are the current experimental limits from CDMS [30]. According to our results the bino scenario is already ruled out, while in the singlino case the upper region can be probed by future experiments. In Fig. 5 we show the reheating temperature after inflation as a function of the neutralino/gravitino mass. The blue region corresponds to a bino, the blue points correspond to singlino, and finally the red points correspond to singlino with relatively high values of the cross-section, namely $\sigma_{\chi-N} > 10^{-47}\ cm^2$. The largest values of T_R correspond to a bino, which is ruled out, and for the singlino with relatively high values of cross-section we obtain a reheating temperature $T_R \simeq 5 \times 10^9\, GeV$ for a neutralino/gravitino mass $m_\chi \simeq m_{\tilde{G}} \simeq 200\, GeV$. In the last figure we show the (m_0-$m_{1/2}$) plane (m_0 and $m_{1/2}$ in GeV) for singlino points with a cross-section larger than $10^{-47}\ cm^2$, or lower than $10^{-47}\ cm^2$. We see that m_0 is not larger than 600 GeV, and therefore future direct detection experiments cannot probe a region of the parameter space which can neither be probed by LHC.

Before ending the discussion, let us briefly comment on a possible collider signature of our model. In the singlino-like neutralino case, where the coupling λ is small, $\lambda \leq 0.01$, the lightest Higgs can be very light, $m_h < 60$ GeV, which has a significant singlet composition, thus escaping detection and being in agreement with accelerator data. In this case the next-to-lightest Higgs is the SM-like Higgs, with a mass $m_H \simeq (116 - 118)$ GeV, and the decay channel $H \rightarrow hh$ is kinematically allowed. Since the lightest Higgs is expected to exit the detector without been seen, the decay channel $H \rightarrow hh$ is an invisible one. This is to be contrasted with the cases of SM and of the MSSM, where the Higgs (in the SM) and the SM-like Higgs (in the MSSM) with a mass in the above range decays (almost entirely) into $b\bar{b}$ and $\tau^+\tau^-$, with the sum of the two branching ratios being practically one [31]. In Table 1 we show the range of the parameters of the model where we obtain a very light Higgs and the decay channel $H \rightarrow hh$ is kinematically allowed. For most of the points the branching ratio is negligible, even as low as $\sim 10^{-9}$, but points exist for which the branching ratio becomes sizable, $BR \sim 0.1$, with the maximum value obtained being $BR(H \rightarrow hh) = 0.13$. In Table 2 we show the Higgs boson masses M_H, M_h and the branching ratio for four points.

λ	$tan\beta$	A_0 (GeV)	A_k (GeV)	m_0 (GeV)	$M_{1/2}(GeV)$
0.0102	34.89	-127.24	-106.41	124.28	606.5
0.000127	25.49	-225.09	-170.8	10.6	401.43

Table 1: Range of the parameters of the model where the decay channel $H \to hh$ is kinematically allowed. The last row shows the minimum value, while the row in the middle shows the maximum value of the parameters.

λ	$tan\beta$	A_0 (GeV)	A_k (GeV)	m_0 (GeV)	$M_{1/2}$ (GeV)	M_H (GeV)	M_h (GeV)	$BR(H \to hh)$
0.000107	34.69	-202.66	-115.23	22.65	581.2	116.97	54.81	3.4×10^{-9}
0.00216	30.25	-158.28	-135.98	49.33	467.87	115.8	46.8	2.82×10^{-4}
0.009154	32.3	-181.5	-131.01	16.2	540.57	118.33	49.44	0.13
0.005064	30.94	-185.46	-169.65	35.86	552.87	117.29	57.17	0.01

Table 2: Higgs boson masses, the branching ratio and the values of the parameters for four points.

4 Conclusions

In the framework of NMSSM, which solves the μ problem, we have assumed that the gravitino LSP and the lightest neutralino NLSP are degenerate in mass. Under this assumption the neutralino becomes extremely long-lived avoiding the BBN bounds. In this scenario we have a two component dark matter made out of the absolutely stable gravitino and the quasi-stable neutralino. We have performed a random scan over the whole parameter space keeping the points that satisfy the available collider constraints plus the WMAP bound for dark matter. These points correspond to either a bino or a singlino neutralino. We have computed the neutralino-nucleon spin-independent cross section as a function of the neutralino mass and the lightest Higgs mass, and we find that the bino case is ruled out (see Fig. 3 and Fig. 4). Then we explored the $(m_0 - m_{1/2})$ parameter space, and the reheating temperature dependence of the neutralino/gravitino mass for the singlino points that correspond to cross section values to be probed by future experiments. Finally, we have briefly discussed an interesting possibility for collider signatures, namely the possibility of having an invisible decay channel $H \to hh$, where H is the SM-like Higgs and h is the lightest Higgs that escapes detection, with a sizable branching ratio and maximum allowed value $BR(H \to hh) \simeq 0.13$.

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References

[1] K. A. Olive, arXiv:astro-ph/0301505;
C. Munoz, Int. J. Mod. Phys. A **19** (2004) 3093 [arXiv:hep-ph/0309346].

[2] M. Taoso, G. Bertone and A. Masiero, JCAP **0803** (2008) 022 [arXiv:0711.4996 [astro-ph]].

[3] J. L. Feng, *In the Proceedings of 31st SLAC Summer Institute on Particle Physics: Cosmic Connection to Particle Physics (SSI 2003), Menlo Park, California, 28 Jul - 8 Aug 2003, pp L11* [arXiv:hep-ph/0405215].

[4] H. P. Nilles, Phys. Rept. **110** (1984) 1;
H. E. Haber and G. L. Kane, Phys. Rept. **117** (1985) 75;
J. Wess and J. Bagger, *Supersymmetry and supergravity* (Princeton University Press, Princeton, 1992);
S. P. Martin, arXiv:hep-ph/9709356.

[5] J. E. Kim and H. P. Nilles, Phys. Lett. B **138** (1984) 150.

[6] H. P. Nilles, M. Srednicki and D. Wyler, Phys. Lett. B **120** (1983) 346;
J. R. Ellis, J. F. Gunion, H. E. Haber, L. Roszkowski and F. Zwirner, Phys. Rev. D **39** (1989) 844;
M. Drees, Int. J. Mod. Phys. A **4** (1989) 3635;
U. Ellwanger, M. Rausch de Traubenberg and C. A. Savoy, Phys. Lett. B **315** (1993) 331 [arXiv:hep-ph/9307322];
U. Ellwanger, M. Rausch de Traubenberg and C. A. Savoy, Z. Phys. C **67** (1995) 665 [arXiv:hep-ph/9502206];
U. Ellwanger, M. Rausch de Traubenberg and C. A. Savoy, Nucl. Phys. B **492** (1997) 21 [arXiv:hep-ph/9611251];
T. Elliott, S. F. King and P. L. White, Phys. Lett. B **351** (1995) 213 [arXiv:hep-ph/9406303];
S. F. King and P. L. White, Phys. Rev. D **52** (1995) 4183 [arXiv:hep-ph/9505326].

[7] R.D.Peccei and H.R.Quinn, Phys. Rev. Lett. 38 (1977) 1440;
R.D.Peccei and H.R.Quinn, Phys. Rev. D 16 (1977) 1791;
S.Weinberg, Phys. Rev. Lett. 40 (1978) 223;
F.Wilczek, Phys. Rev. Lett. 40 (1978) 279.

[8] L. Covi, J. E. Kim and L. Roszkowski, Phys. Rev. Lett. **82** (1999) 4180 [arXiv:hep-ph/9905212];
L. Covi, H. B. Kim, J. E. Kim and L. Roszkowski, JHEP **0105** (2001) 033 [arXiv:hep-ph/0101009].

[9] G. Jungman, M. Kamionkowski and K. Griest, Phys. Rept. **267** (1996) 195 [arXiv:hep-ph/9506380].

[10] J. R. Ellis, A. D. Linde and D. V. Nanopoulos, Phys. Lett. B **118** (1982) 59;
M. Y. Khlopov and A. D. Linde, Phys. Lett. B **138** (1984) 265.

[11] J. Ellis and K. Olive, Phys. Lett. B 514 (2001) 114;
H. Baer and A. Box, Eur. Phys. J. C 68 (2010) 523;
H. Baer, A. Box and H. Summy, arXiv:1005.2215 (2010).

[12] M. Kawasaki, K. Kohri and T. Moroi, Phys. Lett. B **625** (2005) 7 [arXiv:astro-ph/0402490].

[13] W. Buchmuller, P. Di Bari and M. Plumacher, Nucl. Phys. B **643** (2002) 367 [Erratum-ibid. B **793** (2008) 362] [arXiv:hep-ph/0205349];
G. F. Giudice, A. Notari, M. Raidal, A. Riotto and A. Strumia, Nucl. Phys. B **685** (2004) 89 [arXiv:hep-ph/0310123].

[14] J. L. Feng, S. Su and F. Takayama, Phys. Rev. D **70** (2004) 075019 [arXiv:hep-ph/0404231];
L. Roszkowski, R. Ruiz de Austri and K. Y. Choi, JHEP **0508** (2005) 080 [arXiv:hep-ph/0408227];
D. G. Cerdeno, K. Y. Choi, K. Jedamzik, L. Roszkowski and R. Ruiz de Austri, JCAP **0606** (2006) 005 [arXiv:hep-ph/0509275].

[15] L. Boubekeur, K. Y. Choi, R. Ruiz de Austri and O. Vives, JCAP **1004** (2010) 005 [arXiv:1002.0340 [hep-ph]].

[16] P. Fayet, "Spontaneously Broken Supersymmetric Theories Of Weak, Electromagnetic And Strong Interactions," Phys. Lett. B **69**, 489 (1977);
S. Dimopoulos and H. Georgi, "Softly Broken Supersymmetry And SU(5)," Nucl. Phys. B **193** (1981) 150.

[17] S. Dimopoulos and D. W. Sutter, "The Supersymmetric Flavor Problem," Nucl. Phys. B **452** (1995) 496 [arXiv:hep-ph/9504415].

[18] D. G. Cerdeno, C. Hugonie, D. E. Lopez-Fogliani, C. Munoz and A. M. Teixeira, JHEP **0412** (2004) 048 [arXiv:hep-ph/0408102];
D. G. Cerdeno, E. Gabrielli, D. E. Lopez-Fogliani, C. Munoz and A. M. Teixeira, JCAP **0706** (2007) 008 [arXiv:hep-ph/0701271].

[19] C. Hugonie, G. Belanger and A. Pukhov, JCAP **0711** (2007) 009 [arXiv:0707.0628 [hep-ph]];
A. Djouadi, U. Ellwanger and A. M. Teixeira, Phys. Rev. Lett. **101** (2008) 101802 [arXiv:0803.0253 [hep-ph]].

[20] E. Komatsu *et al.* [WMAP Collaboration], Astrophys. J. Suppl. **180** (2009) 330 [arXiv:0803.0547 [astro-ph]].

[21] M. Bolz, A. Brandenburg and W. Buchmuller, Nucl. Phys. B **606** (2001) 518 [arXiv:hep-ph/0012052].

[22] J. Pradler and F. D. Steffen, Phys. Rev. D **75** (2007) 023509 [arXiv:hep-ph/0608344].

[23] V. S. Rychkov and A. Strumia, Phys. Rev. D **75** (2007) 075011 [arXiv:hep-ph/0701104].

[24] U. Ellwanger, J. F. Gunion and C. Hugonie, JHEP **0502** (2005) 066 [arXiv:hep-ph/0406215];
U. Ellwanger and C. Hugonie, Comput. Phys. Commun. **175** (2006) 290 [arXiv:hep-ph/0508022];
G. Belanger, F. Boudjema, C. Hugonie, A. Pukhov and A. Semenov, JCAP **0509** (2005) 001 [arXiv:hep-ph/0505142].

[25] S. Heinemeyer, "Electroweak precision data and gravitino dark matter," arXiv:hep-ph/0611372.

[26] W. M. Yao *et al.* [Particle Data Group], "Review of particle physics," J. Phys. G **33** (2006) 1.

[27] E. Cremmer, S. Ferrara, L. Girardello and A. Van Proeyen, Nucl. Phys. B **212** (1983) 413.

[28] J. R. Ellis, K. A. Olive, Y. Santoso and V. C. Spanos, Phys. Lett. B **588** (2004) 7 [arXiv:hep-ph/0312262].

[29] J. R. Ellis, A. Ferstl and K. A. Olive, Phys. Lett. B **481** (2000) 304 [arXiv:hep-ph/0001005].

[30] Z. Ahmed *et al.* [The CDMS-II Collaboration], Science **327** (2010) 1619 [arXiv:0912.3592 [astro-ph.CO]].

[31] A. Djouadi, Phys. Rept. **457** (2008) 1 [arXiv:hep-ph/0503172];
A. Djouadi, Phys. Rept. **459** (2008) 1 [arXiv:hep-ph/0503173].

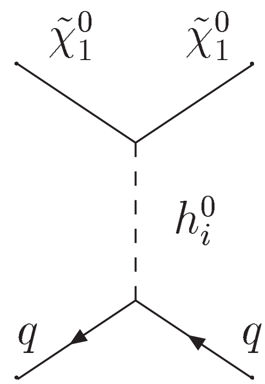

Figure 1: Neutralino scattering off a nucleon by a neutral Higgs boson exchange.

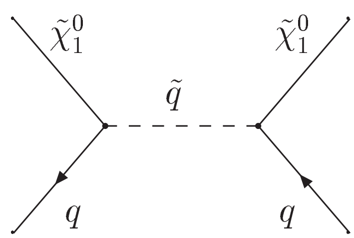

Figure 2: Neutralino scattering off a nucleon by a squark exchange.

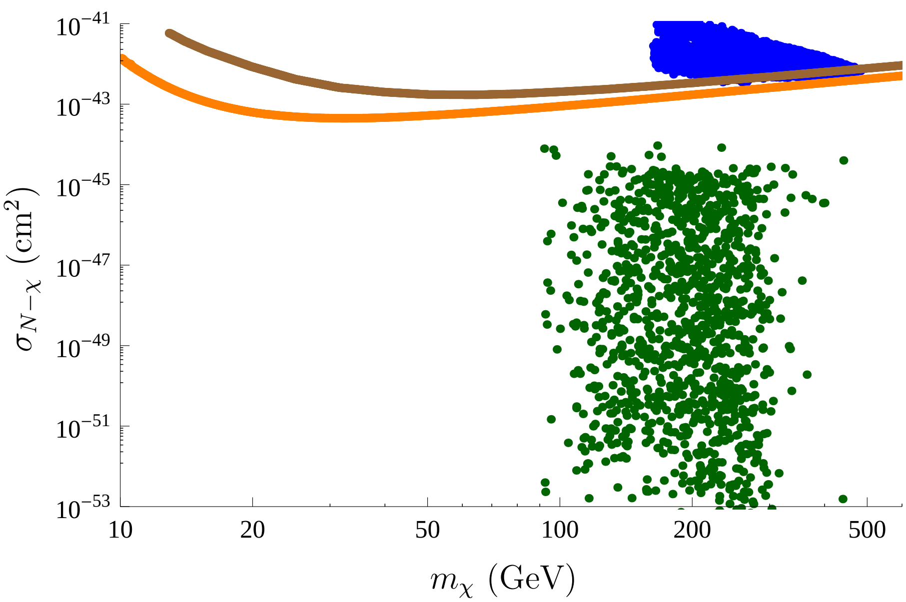

Figure 3: Spin-independent neutralino-nucleon (proton) cross-section versus neutralino mass. Shown are the available experimental bounds from CDMS, and the predictions of the theoretical model. The blue region corresponds to a bino-like neutralino, while the green points correspond to a singlino-like neutralino.

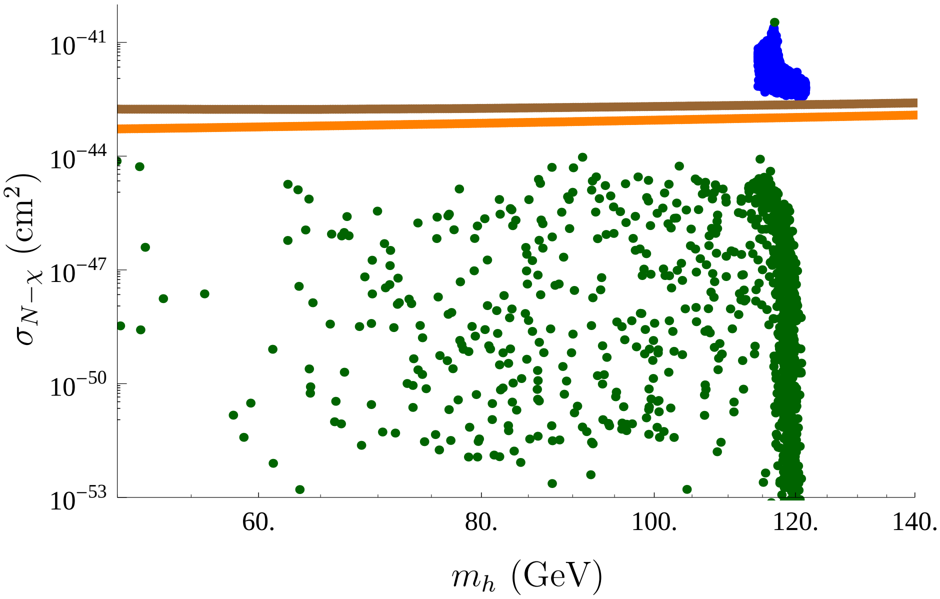

Figure 4: Spin-independent neutralino-nucleon (proton) cross-section versus the lightest Higgs mass. Shown are the available experimental bounds CDMS, and the predictions of the theoretical model. The blue region corresponds to a bino-like neutralino, while the green points correspond to a singlino-like neutralino.

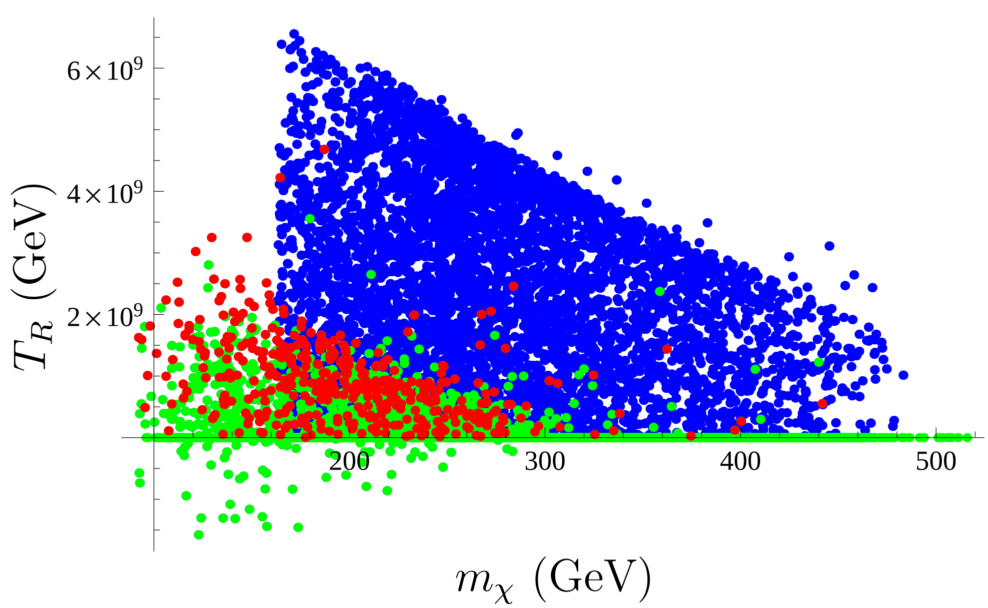

Figure 5: Reheating temperature versus neutralino (or gravitino mass). Blue points correspond to bino, green points correspond to singlino, and red points correspond to singlino with a cross-section larger than 10^{-47} cm^2.

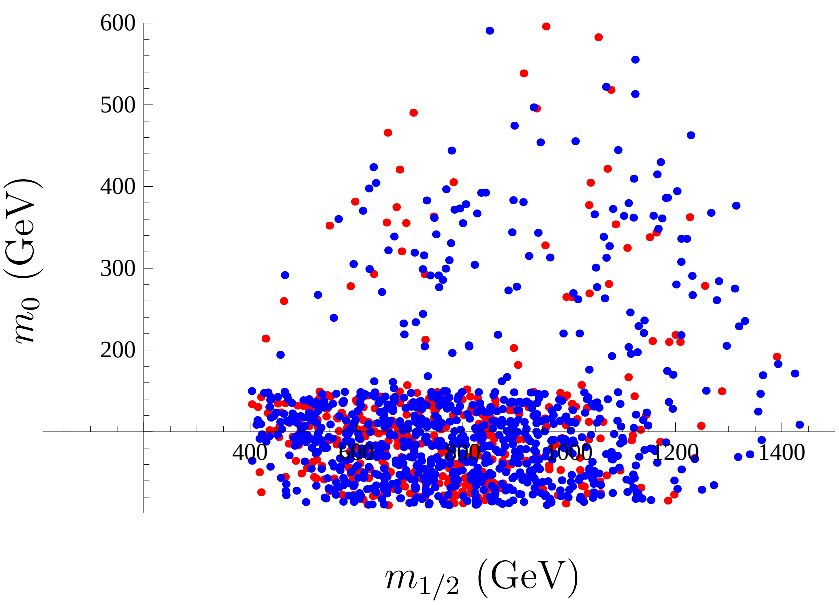

Figure 6: The (m_0-$m_{1/2}$) plane for the singlino points. One color corresponds to a cross-section larger than 10^{-47} cm^2, and the other color corresponds to a cross-section lower than 10^{-47} cm^2.